Effect of Architecture on the Resistivity of Carbon Fiber Polymer Composites

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ABSTRACT

The electrical resistivity of carbon fiber laminar composites can be tailored by weave direction, fiber composition, resin composition, applied pressure, and fiber fraction. Although the weave direction was only found to be important in the case of high aspect ration composites, the other factors were found to influence the resistivity generally. Most intriguing, the resistivity of composites with lamina of different fiber compositions follows a parallel resistor model. This opens the door for higher performance, lower cost composites to be fabricated from these mixed fiber composites.

Introduction

It has been suggested that laminar carbon fiber polymer composites be utilized for applications where a light-weight, high-strength, stiff electrical conductor is needed. This is particularly true for weight-critical aerospace applications, such as electromagnetic interference (EMI) shielding and ground return busses.[1,2] It has been generally assumed for composites formed using woven fabrics that the electrical properties of these materials are homogeneous, at least in the laminate direction. It has recently been shown that, while this is generally a valid assumption, the fiber geometry becomes important when any portion of the piece size starts to become of the order of a few times the tow size.[3] This result raises further questions about the influence of the weave pattern on the resistivity of composite structures. Specifically, this study is concerned with the effect of orientation of the weave in adjacent layers, the influence of layering fibers of different resistivity in a single laminate, the dielectric constant of the resin, and the influence of the local fiber fraction. Space prohibits a full reporting of the results here, so only a few of the results will be discussed. Further results, of this study, including the effects of resin dielectric constant and applied pressure will be reported in detail elsewhere.[4]

Methods and Materials

Thornel® pitch-based carbon fibers (Cytec) with a variety of resistivity values were used in this study. These included P-100, P-55, and P-100 fibers intercalated with bromine (Br_2). The bromine intercalation reactions used to synthesize these fibers have been described in detail elsewhere.[5] The resistivity of each of the fiber types was measured for at least a dozen individual fibers samples from at least two different sections of the fabric using a constant-current four-point method at both polarities. Details are again found elsewhere.[5] The resistivities of the fibers used in this study are shown in Table I.

Table I

Fiber Type	ρ, $\mu\Omega$-cm
P-55	900 ± 100
P-100	330 ± 60
P-100+Br_2	55 ± 7

Composites were fabricated using two thermoset resins, epoxy and polyisocyanate, and two thermoplastic resins, polystyrene and acrylonitrile butadiene styrene copolymer (ABS). Composites with one to six plies were fabricated in a variety of weave orientations and fiber compositions. Composites that are referred to as homogeneous were made with a single type of fiber, while those referred to as heterogeneous were made with two types of fibers.

Measuring the resistivity of composite materials as inhomogeneous as these is not straightforward. Two different methods were used, and the results were somewhat different. The first was a contact-less eddy current method, utilizing a Leheighton Model 1010A conductivity probe which was factory modified to operate at 55.55 kHz. This method has the advantage of not requiring electrical contacts, the most common source of experimental difficulty and error in any electrical measurement. The disadvantage is that the theory developed for interpreting the data assumes that the material being measured is homogeneous, which these composite most certainly are not. This method also enables the easy mapping of the resistivity of the composites, and so gives information on the homogeneity of their resistivity. The second method was the constant current four-point method, which has the advantage of a more straight-forward interpretation of the data. As long as the sample size is large with respect to the scale of the inhomogeneity, the result of the measurement is unambiguously the bulk resistivity of the sample. The relative merits of the two measurements, as well as the more accurate multi-point method, have been discussed previously.[3]

Results

The orientation of the weave with respect to the current direction has no apparent effect on the resistivity of the composites, as long as the dimension of the composites is large with respect to the fiber tow. This finding of a previous study[3] was confirmed to be true under an even wider variety of geometries than previously reported, but will not be further discussed here.

The composite resistivity was found to be very sensitive to the local fiber fraction of the composite. This is illustrated in Figure 1 which shows the eddy current resistivity of three different 1-ply composites of P100 fabric in ABS matrix. Under the assumption that the amount of fiber in the woven fabric is constant, the thickness variation is due entirely to local variations in the amount of resin. Although there is considerable scatter in the data, the resistivity varies with thickness in essentially the same way in all three composites, all increasing with thickness, or a local decrease in fiber fraction. This probably reflects the contact area between adjacent fibers both within a tow and between tows.

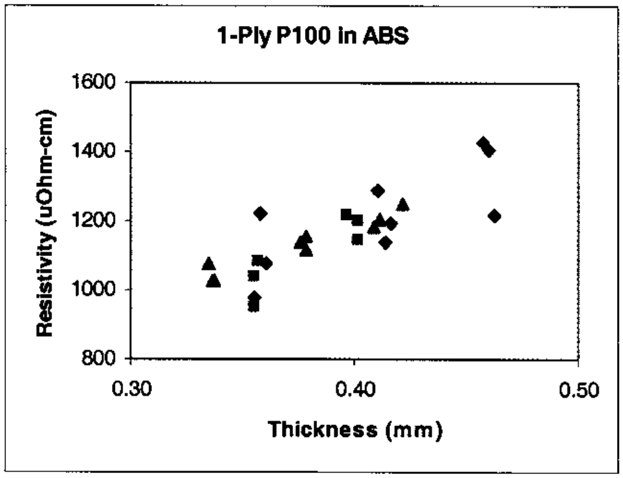

Figure 1 – The resistivity as a function of thickness for three different single ply composites of P100 in ABS. Measurements from each individual composite are represented by a different symbol.

The number of plies did not effect the resistivity of the composites. When the resistivities of composites made from one to six laminates were plotted as a function of local fiber fraction, they all fell along approximately the same line, similar to that shown in Figure 1.

The resistivity of heterogeneous composites was particularly interesting. This is illustrated in Figure 2, which plots the heterogeneous composite resistivity divided by the corresponding homogeneous pristine composites resistivity as a function of the fraction of plies that are made with bromine intercalated P100 fibers. The three to six ply composites all fall along the same curve. Thus, the resistivity of a four-ply laminate with two plies of bromine intercalated fiber is essentially the same as a six-ply laminate with three plies of intercalated fiber.

It is also clear that the relationship is not linear. In the cases sighted above when half of the layers are intercalated, the resulting resistivity is not the mean of the pristine fiber layers and the intercalated fiber layers (about 0.63 of the pristine resistivity) but instead a much lower value (about 0.40 of the pristine). Inspection of the data reveals that it closely follows a parallel plate model, the results of which are shown as the line in Figure 2.

This model assumes that the resistance between the lamina is much greater that the resistance within them. This results in the current flowing through the composite like a set of resistors in parallel. If the resistance between the layers and within the layers was comparable, the result would be an essentially homogeneous composite, with a resistance equal to the average resistance of the fibers, which is clearly inconsistent with the data. Thus a greater proportion of the current is transmitted along the more conductive layers than along the less conductive. This has been shown to be true not only for layers of intercalated fibers embedded within layers of pristine fibers, but also for any more conductive layer within a less conductive composite, i.e. P100 layers in a P55 laminate.

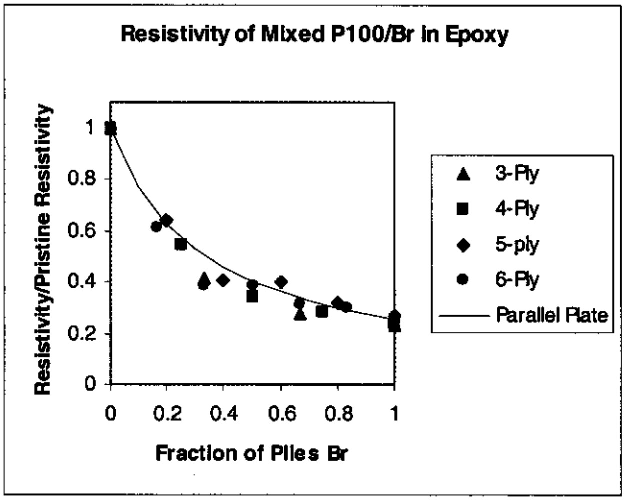

Figure 2 – Composite resistivity/resistivity of a homogeneous pristine P100/ABS composite as a function of the fraction of plies that are intercalated with bromine. The line represents the results of a model that treats each layer as a resistor in parallel to the other layers.

This behavior has interesting technological implications. Heterogeneous composites made up of high performance, very expensive fibers, embedded in lower performance, less expensive fibers can be fabricated to tailor the electrical performance and cost to the need. Further, the parallel plate model enables the prediction of the resistivity of the heterogeneous composites. The implication is that small amounts of high performance fibers will have the most effect if laid into a single layer in the laminate.

References

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